Paper Number

A Miniature Dewpoint Hygrometer for Monitoring Human Environments in Space

M. E. Hoenk, G. Cardell, F. Noca, and R. K. Watson
Microdevices Laboratory
Center for Space Microelectronics Technology
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA

ABSTRACT

Water vapor enjoys unique importance in Earth's atmosphere and human environments in space. In spite of this importance, humidity measurement remains a difficult technological problem, and no single instrument is optimal for all applications. We have developed and demonstrated a high-sensitivity dewpoint hygrometer in flight tests on a small radiosonde balloon and the NASA DC8. This instrument achieves fast response to atmospheric humidity by using a surface acoustic wave (SAW) device to detect condensation with much higher sensitivity than conventional optical dew detectors. An early prototype showed more than an order of magnitude faster response than chilled-mirror hygrometers in tropospheric humidity measurements on the NASA DC8. For the radiosonde experiment, we miniaturized and integrated the SAW hygrometer into a 1 kg package that includes pressure and temperature sensors, GPS, a programmable instrument controller, a high-speed radio modem, and lithium-ion batteries. We flew this instrument to 44,000 feet on a small balloon for a side-by-side comparison with a commercial radiosonde. Design elements of the reference radiosonde are presented, along with a discussion of requirements for a hand-held instrument for NASA's Human Exploration and Development of Space Enterprise.

INTRODUCTION

Water vapor is the most important of the greenhouse gases in Earth's atmosphere, and plays a major role in atmospheric dynamics.[1] *In situ* measurements of water vapor in the atmosphere are needed for studies of weather and climate, as both a primary data source and as ground truth for remote sensing measurements. In spite of its importance, humidity measurement remains a difficult technological problem, and no single instrument or technique is optimal for all applications.[2] Part of the difficulty lies in the enormous range of conditions in which the instruments are required to operate. The water vapor concentration in the atmosphere ranges from several percent at Earth's surface to parts per million in the stratosphere, while ambient temperatures vary over a 100K range and ambient pressure drops several orders of magnitude from the Earth's surface to the upper stratosphere.

Atmospheric profiling of humidity has historically been accomplished with radiosondes. Known problems with the accuracy of radiosonde humidity sensors, as well as the remote-sensing requirement for an accurate ground-truth humidity sensor, have created a need for a radiosonde that incorporates a high-performance microhygrometer.[3] The national weather service launches approximately 80,000 radiosondes every year, and relies heavily on radiosonde data for weather forecasting. In at least one case, erroneous radiosonde data resulted in a failure to predict flood conditions, resulting in loss of life and significant property damage in Ohio. Responding to these problems, meteorologists have called for the development of a reference radiosonde to serve as a standard for comparison of various radiosonde technologies and practices. Such a standard has been elusive. Radiosondes have been flown in conjunction with hygrometers carried on airplanes, along with simultaneous ground-based measurements using microwave radiometers and DIAL systems. These comparisons have identified radiosonde measurement problems (especially near saturation and in cold, dry conditions), but do not allow point-by-point determination of radiosonde measurement errors.

Water vapor's importance extends to space, as one of the most important components of human environments in advanced life support systems and a sensitive indicator of stagnant air in closed atmospheres. Environmental control on the space station relies on circulation to prevent the accumulation of hazardous gases in isolated pockets of air. High local concentrations of water vapor, in addition to posing a risk of condensation, are an indicator of stagnant air. The relative humidity sensors used in commercial hand-held hygrometers are inadequate for this application. With off-the-shelf accuracies typically no better than ±5%RH in the 20-80%RH range, commercially available RH sensors also suffer from hysteresis at high humidities and degradation of accuracy over time. This demanding application requires an accurate, reliable instrument with fast response over a very large range of absolute humidity.

Intrinsically more reliable than relative humidity techniques, dewpoint measurement is commonly employed as a laboratory reference instrument for the measurement of absolute humidity. However, conventional dewpoint hygrometers use chilled mirrors to detect condensation, and are considerably larger than the desired handheld instrument. The SAW hygrometer developed for JPL's reference radiosonde can detect condensation with two orders of magnitude higher sensitivity than the optical methods employed by chilled mirror instruments. In flight experiments conducted on the NASA DC8, SAW hygrometers measured atmospheric humidity transients with a response time over an order of magnitude faster than chilled mirror hygrometers.[4] Recently we integrated a miniature SAW hygrometer (and other sensors, including GPS) into a reference radiosonde, and tested the instrument in flight on a small atmospheric balloon.[5] At its current stage of development, the SAW hygrometer does not meet NASA's requirements for space station instrumentation. Further development is required for improved autonomy, integration into a handheld instrument, and flight qualification.

INSTRUMENT DESCRIPTION

The primary functions of JPL's radiosonde are to periodically measure humidity, pressure, temperature, and position, and to report the measurements over a digital serial connection to a base station. The base station records the serial data stream as received, displays the key parameters on a screen in order to monitor the status, and provides an uplink interface to send commands and update operational parameters used by the environmental station. Behind these basic functions are a number of sophisticated sensors, circuits, and software which provide the accuracy required of a reference instrument, and the flexibility to be configured for a variety of applications. Three custom circuit boards were designed and fabricated, containing the multiplicity of circuits required for this instrument. An RF board contains the radio-frequency oscillator circuits used to drive the surface acoustic wave (SAW) device and provide the outputs for the determination of humidity with the SAW device. An analog board provides signal conditioning, power conditioning, and AD/DA conversion, with appropriate interfaces to both the digital board and the sensors. The digital board provides digital signal processing, digital logic and timing, and asynchronous serial communications, with appropriate interfaces to the analog board, the GPS board, an RS232 device (*e.g.*, the RF modem), and an optional LCD display. In addition to these three custom circuit boards, two commercial circuit boards have been incorporated into the package. A commercial GPS board is used to measure the position of the instrument, and a commercial RF modem is used for full-duplex communications with the base station. The base station provides the user interface, including display of real-time data, a moving map with the position of the instrument shown as a superimposed marker, data storage, and a command/control interface for remote transmission of messages to the instrument. Additional details are provided below.

SENSORS

The sensor suite includes a JPL-developed humidity sensor (the SAW hygrometer), a commercially-available micromachined pressure sensor (the Motorola MPX4115), and three commercially-available, fast-response thermistors (Thermometrics FP07-DB-103-N). Measurements are made with using sigma-delta A/D converters with built-in self-calibration capability (AD7714). The pressure sensor has a voltage output, which is measured by the A/D converter through a low-pass input filter, and sampled using the 5V pressure sensor supply voltage as a reference. The temperature sensors are measured using simple voltage dividers, using a stable 1Mohm resistor as a reference.

The SAW hygrometer has been previously patented.[6,7] The essence of this sensor, which drove many of the designs due to the sophistication of its requirements, has not changed since the patent was filed. However, some new circuits were developed to enable miniaturization and achieve improved performance. The SAW hygrometer is an active sensor, using digital feedback control of the device temperature to measure dewpoint. In operation, the SAW output is measured and compared with the programmed calibration parameters to determine the amount of condensation on the surface and provide a feedback signal to adjust the device temperature. Properly calibrated, the feedback controller maintains equilibrium between evaporation and condensation of water/ice on the device surface, so that the device temperature corresponds to the environmental humidity. The sensor itself consists of a surface acoustic wave device (SAW) mounted on a thermoelectric cooler (TEC), which is, in turn, mounted to a heat sink. An integrated temperature-sensitive resistor is used to monitoring the temperature of the SAW device. Supplying current to the TEC heats or cools the SAW device, depending on the polarity of the current. An impedance-matched RF-amplifier circuit drives the SAW device. The output of SAW device is amplified and fed into the SAW input, so that the circuit oscillates at a frequency determined by the high-Q resonance of the

SAW device. This resonant frequency and loss through the SAW are highly sensitive to condensation on the SAW surface, and to the device temperature. The circuit provides both a frequency output (at approximately 249.6 MHz) and two low-frequency voltages related to the RF amplitudes at the input and output of the SAW device. The frequency output is conditioned by a mixer circuit, which uses a temperature-stabilized 50 MHz oscillator as a reference, producing an intermediate frequency of approximately 0.3-0.7 MHz. This frequency represents the difference between the fifth harmonic of the reference oscillator (250 MHz) and the SAW frequency (variable, between approximately 249.4 and 249.7 MHz). The mixer output frequency, which is sensitive to both temperature and condensation on the SAW surface, is measured by a field-programmable gate array (FPGA). A phase-sensitive period-counting technique implemented in the FPGA enables measurement of the SAW frequency with a resolution of a few Hertz at a sample rate of approximately 100 Hz. In addition, the SAW input and output amplitudes are measured by monitoring the voltage across a 10kohm load resistor on each of the outputs. The input amplitude depends primarily on the saturation properties of the amplifiers in the RF oscillator circuit, while the output amplitude is sensitive to the loss through the SAW device, thus providing an alternate way to monitor condensation on the SAW device. The temperature of the SAW device is measured using a resistor deposited by the SAW manufacturer on one edge of the SAW device. As this is a critical measurement both for accurate humidity measurement and stable feedback control of the SAW temperature, an ultrastable resistor is used as a reference to obtain 16-bit resolution.

DIGITAL CONTROLLER

Measurement, control, and interface functions are implemented in a compact package using an advanced digital signal processor (DSP) and a field-programmable gate array (FPGA). One of the key functions of the digital controller is to provide active digital feedback to the SAW microhygrometer, enabling highly flexible, programmable control of the equilibrium condition necessary for dewpoint/frostpoint measurement. These functions incorporate a high degree of autonomy, with the flexibility to alter the automatic functions and operational parameters through software. The DSP collects the digital data, performs local data processing, sets voltages output through the two DACs, generates formatted output messages containing data and other operational parameters, monitors system health, responds to error conditions, and receives, interprets, and responds to formatted serial input messages. The FPGA implements several low-level functions in hardware, which frees the digital signal processor for the more critical tasks. For example, commands and data are transferred to and from the ADCs and the DACs through a serial digital interface at a relatively low frequency. This serial interface is implemented in the gate array such that the DSP can read and write data to the ADCs and DACs as though they were a set of registers in I/O space, without worrying about timing. Moreover, the FPGA generates an interrupt to the processor whenever data is ready, so that the processor does not waste clock cycles polling devices between measurements. Finally, the counters used by the instrument are implemented directly in the FPGA, with programmable parameters appearing as registers in I/O space and processor interrupts being generated as data becomes available.

POWER CONDITIONING

Batteries power the instrument through efficient conditioning circuits. Power conditioning consists of switching power supplies (for maximum efficiency) and low-pass filters. Low-noise measurements required the use of large capacitors and inductors in the power supply filters, as well as careful circuit layout and shielding. Three D-sized lithium sulfur chloride batteries were connected in series to power the instrument, with a loaded voltage output of approximately 10 volts, and a maximum output current of 3 amps. The batteries were chosen to have sufficient energy storage and peak current capability for a two-hour flight at full power, followed by an extended period of low-power operation during the recovery stage of the experiment. To reduce the overall size and mass of the instrument, nearly all of the circuits were designed for a single-ended 5 volt supply. The exceptions are the TEC driver circuit (described below) and the RF oscillator circuit. Although a 5 volt version of the RF oscillator circuit has been built and tested, the field experiments conducted up until now have required a 12 volt supply. Lower power could be achieved by reducing the voltage (particularly in the digital circuits), but for the radiosonde application the choice of batteries was driven largely by the high peak current required during RF transmission.

The temperature of the SAW device is controlled by a two-stage thermoelectric cooler, which can require several watts of power under some conditions; therefore, the TEC driver circuit must be as efficient as possible in order to conserve battery power. A DAC interfaced to the digital signal processor through the FPGA sets the voltage to be delivered to the TEC. This voltage controls the output of a switching power supply, which efficiently converts the circuit battery supply voltage (8-12V) to the desired voltage to drive the TEC (0-2V for the TEC used in this implementation). The voltage supply is single-ended - in order to provide heating as well as cooling, a switching circuit is provided which reverses the polarity of the voltage output to the TEC, in response to the sign of the digital value set by the digital signal processor. The FPGA provides a hardware interface, which automatically responds to the sign of the parameter sent by the processor by setting the polarity of the output appropriately. Finally, the TEC driver circuit is automatically disabled when the SAW device rises above a threshold temperature, which is adjusted by a variable resistor located on the analog board. This circuit is implemented in hardware to prevent damage to the TEC by overheating.

RADIOSONDE INTEGRATED INSTRUMENT

In addition to the sensors and conditioning circuits, the radiosonde instrument requires RF communications, GPS position measurement, flight termination hardware, and an enclosure, which were implemented as described below.

Communications

Radio communications between the instrument and the base station were implemented through a Freewave DGRO-115 RF modem with a maximum data throughput of 115 kbaud and a maximum transmitted power of 1 Watt. The Freewave modem operates in the 902-928MHz band, using frequency-hopping spread spectrum communications for reliable, line-of-sight communications in a possibly noisy environment. All transmissions are message-based, with header and data portions separately encoded with checksums to ensure data integrity. Handshaking was implemented to prevent data collisions between the two ground stations during the balloon test.

GPS Position Measurement

The position of the package is monitored using the global positioning system (GPS). A Rockwell Jupiter board, connected to a GPS antenna with a built-in amplifier, receives coded transmissions from Earth-orbiting GPS satellites, and uses this data to calculate the position of the instrument once per second. A connector and cable from the digital board provides the power and asynchronous RS232 interface required to interface the Jupiter board to the digital controller. Software implemented in the DSP collects data from the Jupiter board and sends the measured position to the base station. The DSP has also been programmed to send commands to the Jupiter board through the serial interface, thereby providing access to the Jupiter board's configuration parameters and allowing operations such as system reset.

Radiosonde Environmental Interface and Enclosure

The radiosonde design depended on flow generated by the upward motion of the balloon to provide both air exchange to the sensor and heat transfer from the TEC. The SAW device was mounted on the upper end of the enclosure, centered in a carefully designed flow channel. The flow was divided at the elliptical leading edge of the SAW mount. The upper part of the flow was designed for laminar flow across a stainless steel plate, with the SAW mounted at the center. Stainless steel was used to minimize outgassing in the dry environment of the upper troposphere. The lower part of the flow was designed for maximal heat exchange, to allow the cold air of the upper troposphere to assist the TEC in obtaining measurements at the lowest possible frostpoints.

The five circuit boards, two antennae, and five sensors were mounted in an aluminum frame designed for high strength and low mass. The batteries were clamped between two aluminum brackets, and mounted on one side of the package. The pressure sensor was located inside the package along with one of the thermistors. The other two thermistors were mounted to extend out the sides of the package, for two independent measurements of air temperature. Surrounding the electronics enclosure, a styrofoam case provided insulation and relative temperature stability during the test flight, while leaving the SAW flow plate and the two external temperature sensors exposed to the environment.

Cutdown

Although not strictly required by FAA guidelines and not normally implemented for commercial radiosondes, terminating the flight on command served as a useful means of selecting a landing area suitable for recovering the payload. The means for terminating the flight involved cutting the instrument away from the balloon, either automatically generated by the digital controller based on preprogrammed criteria (*e.g.*, elapsed time or GPS position), or remotely through a command from the base station. Once commanded, cutdown was implemented by activating a nichrome wire heater circuit designed to melt through the parachute cord connecting the payload to the balloon. An independent battery supplied enough current to the heater to melt through the cord within a few seconds of activation. Once the balloon was cut free, the downward motion caused a parachute to open, and the payload drifted to Earth at a modest rate of descent.

FLIGHT TESTS

The JPL radiosonde was flown on a small balloon to an altitude of 44,000 feet on April 23, 1998.[8] The balloon was launched at 16:27 UCT from the top of a hill overlooking a small airfield outside of Hatch, New Mexico. Approximately 42 minutes after launch, a command was transmitted from the mobile ground station to the radiosonde to cut the balloon free, allowing payload to begin a parachute-controlled descent. Approximately 30 minutes later, the payload touched down in White Sands Missile Range. Using GPS position data, the payload was successfully recovered within an hour, 50 miles from the launch site. The SAW microhygrometer reported a minimum frostpoint of -76°C, corresponding to approximately 6 ppm of water vapor at this altitude. The data suggest that the SAW microhygrometer is capable of measuring humidity at still greater altitudes, perhaps as high as the tropopause. *In* *situ* measurements of humidity in this scientifically critical region of the atmosphere are needed for studies of the Earth's atmosphere and climate.

Following the successful radiosonde flight test, the SAW hygrometer was deployed on the NASA DC8 for humidity measurements in Atlantic hurricanes during the 1998 season, as part of the NASA-sponsored Convection and Moisture Experiment (CAMEX-3).[9]

HUMIDITY MEASUREMENTS IN SPACE

Instrumentation for use in human environments in space must pass a rigid qualification and documentation procedure, which requires considerable time and expense to complete, and often involves mandatory modifications to the instrument design.[10] Safety and reliability are key concerns addressed in this process, because the measurements involve issues related to environmental safety, and the data may affect high-level operations and schedules.

In addition to the qualification requirements noted above, the design and packaging of the SAW hygrometer must be modified and optimized for the specific measurement environment appropriate to the space station.[11] The primary application being considered is a handheld instrument for local monitoring. Of primary concern are local concentrations of water vapor that approach saturation, which may indicate the existence of pockets of stagnant air. Sampling is important in order to get a fast, reliable measurement of local humidity and to filter out any contaminants that might adversely affect the accuracy of the measurement. Additionally, the instrument must be small and operate for long periods of time on batteries. The lithium batteries used on the radiosonde represent an undesirable risk on the space station. A long shelf-life is necessary, as the instrument may lie unused for long periods of time.

Several modifications enabling reduced mass, power, and cost have been identified, and partially implemented. The RF modem and GPS boards can be eliminated from the design, as these are not needed for HEDS applications (the RS232 interface will be retained, enabling A new circuit for driving the SAW at its resonance frequency has been designed, using low-cost surface mount components. This new circuit requires less power, and operates from a 5 volt supply, thereby eliminating the 12 V power conditioning circuit. Modifications to the analog signal conditioning circuits will reduce the component count and save power. Newly available digital components will enable significant reduction in the size, power, and cost of the controller electronics. A new enclosure is needed, which incorporates a visual readout and user interface for handheld operation. Modifications to the controller software are required, implementing improved autonomy and self-calibrationi functions, as well as application-specific command and control functions. The hardware and software modifications must include a provision for an ultra low-power standby mode, in order to extend the battery life. Together, these modifications will enable the use of significantly smaller (and less expensive) batteries, resulting in significant mass reductions with respect to the radiosonde package.

CONCLUSION

In flight tests on a radiosonde balloon and NASA's DC8, the SAW hygrometer measured atmospheric humidity with a response time over an order of magnitude faster than conventional chilled-mirror dewpoint hygrometers. While the SAW hygrometer performed admirably in these experiments, the existing configuration is not suitable for NASA's HEDS applications, which entail a set of requirements distinct from the radiosonde design. Under a small grant from NASA's Advanced Environmental Monitoring Program, we are currently investigating options for meeting these requirements.

ACKNOWLEDGMENTS

The NASA Atmospheric Dynamics and Radiation Program is gratefully acknowledged for initiating and providing continuing support to the research program which led to the development and flight testing of the SAW dewpoint microhygrometer. The research described in this paper was performed at the Center for Space Microelectronics Technology, Jet Propulsion Laboratory, California Institute of Technology, and was jointly sponsored by the National Aeronautics and Space Administration, Earth Science Enterprise, Space Science Enterprise, and Human Exploration and Development of Space Enterprise.

We would like to thank Mr. Steve Woodward of Digital Specialties and Mr. Doug Price of JPL's Communications Ground Systems section for their innovative circuit designs, which were essential in miniaturizing the hygrometer electronics. The authors gratefully acknowledge the efforts of Mr. Charlie Houghton and Professor Bernie McCune of New Mexico State University's Physical Science Laboratory, and Mr. Larry Misquez, Mr. Fred Wilson, Mr. Don Hayes, and Mr. Kenneth Odom of the Weather Support Branch, White Sands Missile Facility, for their superb planning and execution of the balloon launch, and for providing the Vaisala radiosonde and the converted Vaisala data.

REFERENCES

1. "Water Vapor in the Climate System," Special Report, American Geophysical Union, December, 1995 (ISBN 0-87590-865-9).
2. E. J. Amdur, "The Relationship of Humidity Reporting Forms and Humidity Sensors," Humidity and Moisture, Volume 3, pp. 321-326, A. Wexler and W. A. Wildhack, eds., Reinhold Publishing Corp., New York, 1965.

3. W. P. Elliott, D. J. Gaffen, "On the Utility of Radiosonde Humidity Archives for Climate Studies," Bulletin of the American Meteorological Society, 72: 1507-1520, 1991.
4. M. E. Hoenk, G. Cardell, D. Price, R. K. Watson, T. R. VanZandt, D. Y. Cheng, W. J. Kaiser, "Surface Acoustic Wave Microhygrometer," SAE Technical Paper Series, #972388, 27th International Conference on Environmental Systems, Lake Tahoe, NV, July 14-17, 1997.
5. M. E. Hoenk, K. Watson, G. Cardell, F. Noca, "A Miniature Environmental Station: Development and Flight Validation," Nanospace '98, International Conference on Integrated Nano/Microtechnology for Space Applications, Houston, Texas, November 1-6, 1998.
6. Michael E. Hoenk, "Fast, High Sensitivity Dewpoint Hygrometer," U.S. Patent No. 5,739,416, Issued April 14, 1998.
7. T. R. VanZandt, W. J. Kaiser, T. W. Kenny, D. Crisp, "High Performance Miniature Hygrometer and Method Thereof," U.S. Patent No. 5,364,185, Issued Nov. 15, 1994.
8. M. E. Hoenk, R. K. Watson, G. Cardell, "Development and Flight Test of a Fast, Miniature Dewpoint Hygrometer for Radiosonde Measurements of Tropospheric Humidity," 8th Conference on Aviation, Range, and Aerospace Meteorology, 79th Annual AMS Meeting, Dallas, Texas, Jan. 10-15, 1999.
9. CAMEX-3 Mission description and data available at the official website: "http://ghrc.msfc.nasa.gov/camex3/"
10. Advanced Human Support Technologies Flight Project Requirements, NASA Johnson Space Center, in preparation.
11. NASA Publication, "Advanced Environmental Monitoring and Control Program, Technology Development Requirements," 1996.

CONTACT

Point of contact for further information:
Dr. Michael E. Hoenk, Michael.Hoenk@jpl.nasa.gov